Interactive Visual Analysis of Flow Data

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Flows

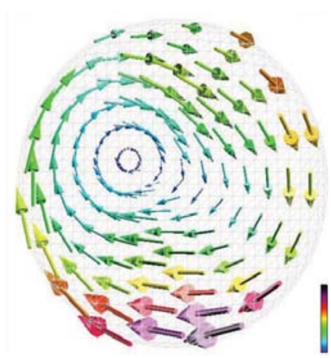
- **Something moving**,
  usually some matter (a liquid or gas),
  but also dynamical systems, *etc*.
- Usefully **understood as differential wrt. time**

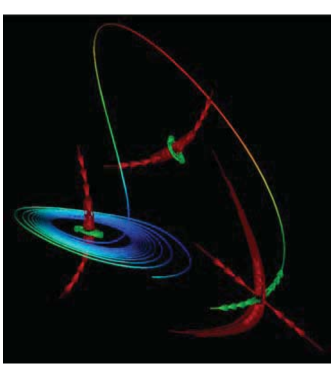
$$\mathbf{v} = \mathrm{d}\,\mathbf{p} \,/\, \mathrm{d}\,t \qquad \mathbf{p} \in \Omega \subseteq \mathcal{R}^n,\ \mathbf{v} \in \mathcal{R}^n,\ t \in \mathcal{R}$$

- Often represented as a **vector field**, *i.e.*,
  as set of vector samples $\mathbf{v}(\mathbf{p}_i)$ over a certain grid $\{\mathbf{p}_i\}$
- Special challenge: unsteady flows $\mathbf{v}(\mathbf{x},t)$: $R^n \times R \rightarrow R^n$
- **Flow data** origin in
  - **measurements**, *e.g.*, with PIV (particle image velocimetry)
  - **simulation**, *e.g.*, from CFD (computational fluid dynamics)
  - **modeling**, *e.g.*, as ODEs (ordinary differential equations)

Flow Visualization Methods

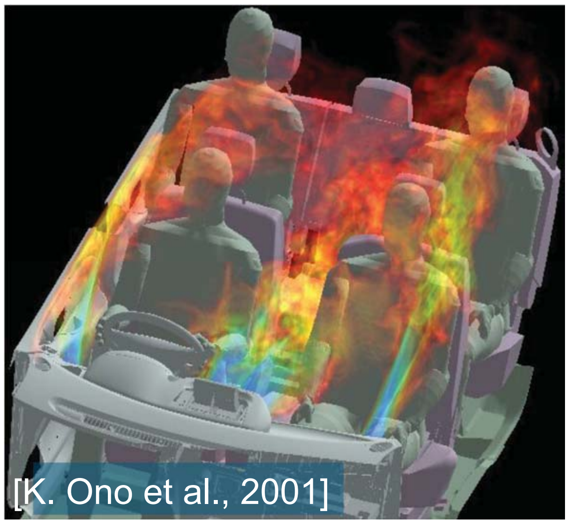
- From Post *et al.*:
  Feature Extraction and Visualisation of Flow Fields
  (Eurographics 2002 State-of-the-Art Report):
  - Direct flow visualization
  - Texture-based flow visualization
  - Integration-based flow visualization
  - Feature-based / topological FlowViz



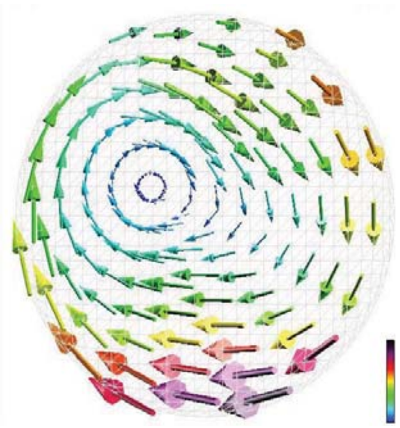


Direct Flow Visualization (1)

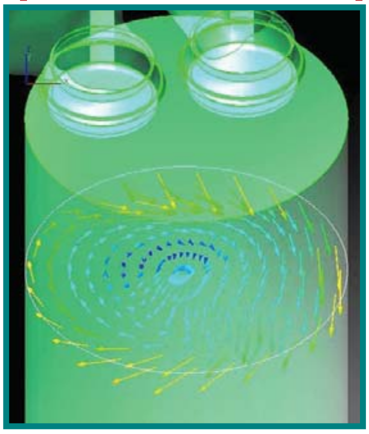
- One-to-one mapping of **v** into vis. space
- Classical approaches:
  - arrows (hedgehog plot)
  - color coding

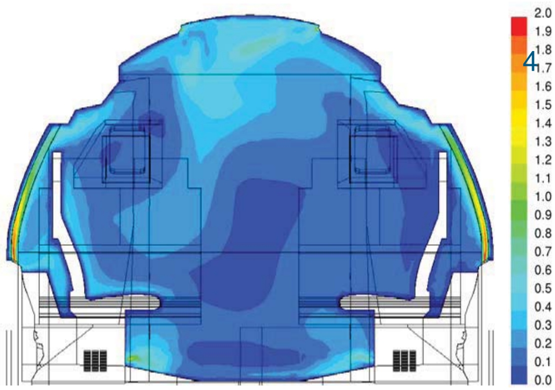


[K. Ono et al., 2001]



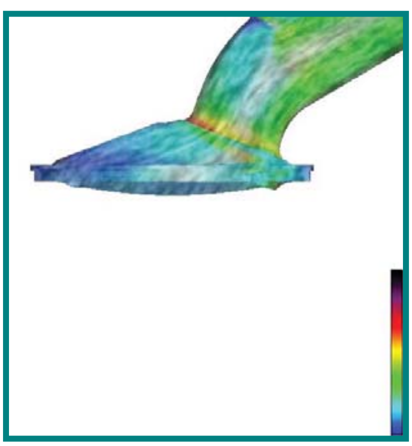
[Laramee et al., 2003]



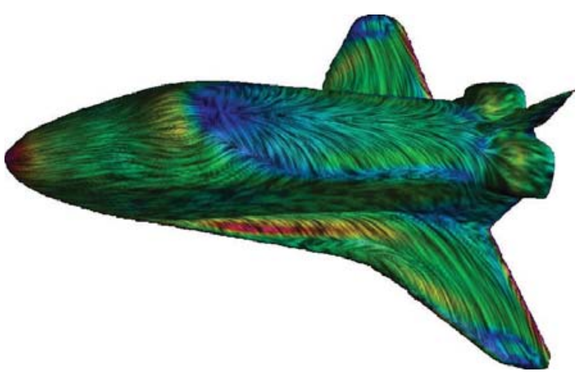


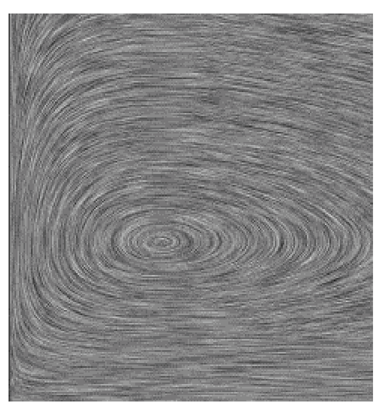
Texture-based FlowVis (2)

- Space-filling vis. of instantaneous flow **v**
- Classical approaches:
  - line integral convolution (LIC) & spot noise
  - texture advection



[Laramee et al., 2003]





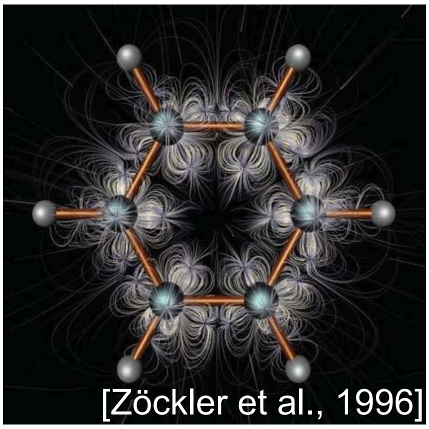
[H. Löffelmann, 1998]

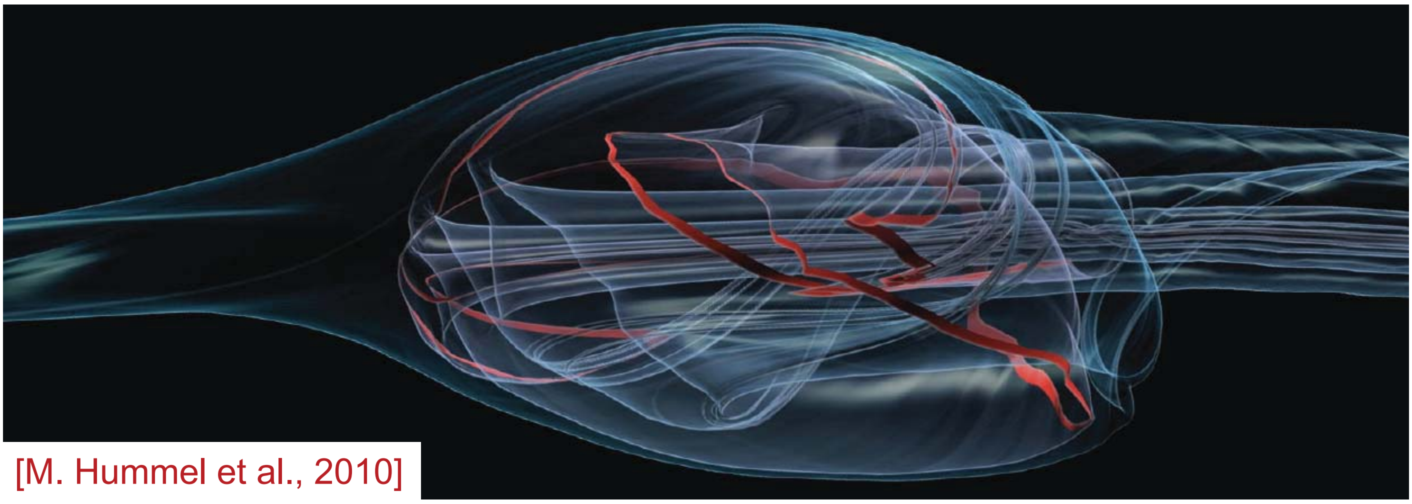
Integration-based FlowVis (3)

- Utilization of integration paths

$$\mathbf{p}(s) = \mathbf{p}_0 + \int_{\tau=0}^{s} \mathbf{v}(\mathbf{p}(\tau),\, t_0+\tau)\,\mathrm{d}\,\tau$$

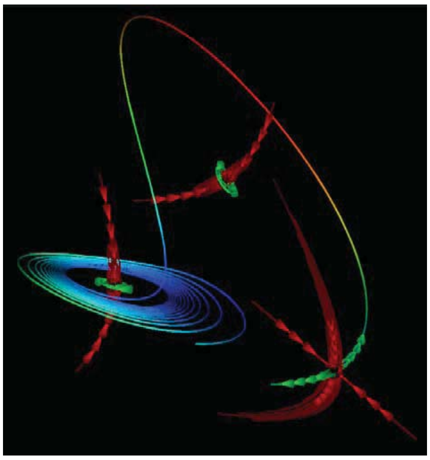
- Classical approaches:
  - streamlines
  - streamsurfaces

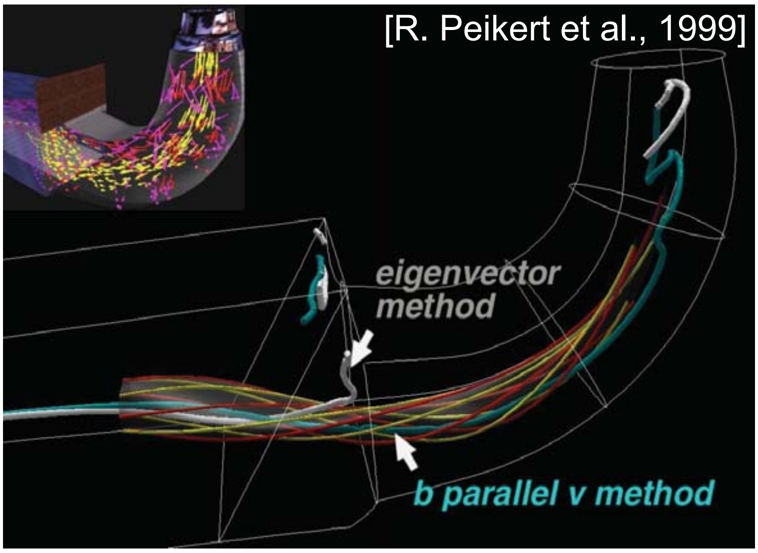

[Zöckler et al., 1996]


[M. Hummel et al., 2010]

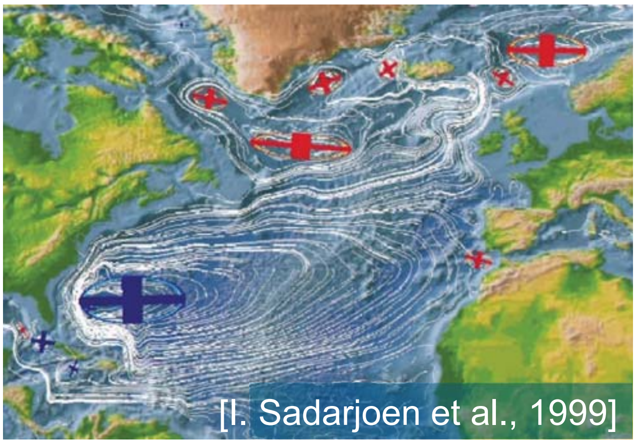
Feature-based / Topological FlowVis (4)

- Computational analysis, then vis.
- Approaches:
  - topology-based FlowVis
  - utilization of vortex extraction for FlowVis


[H. Löffelmann et al., 1998]



[R. Peikert et al., 1999]


[I. Sadarjoen et al., 1999]

Interactive Visual Analysis of Flow Data

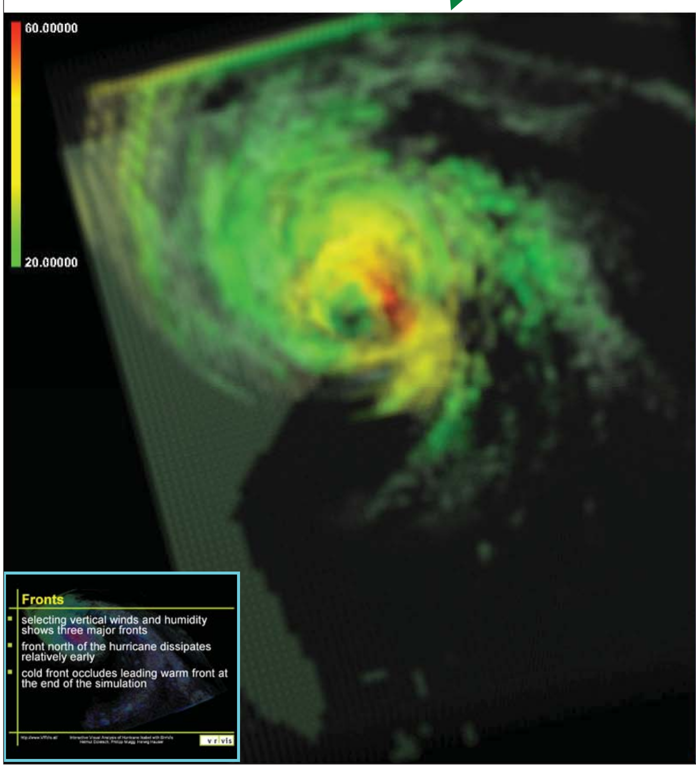
- **Base-level IVA** *(solves many problems, already!)*
  - bring up at **least two different views** on the data
  - allow to **mark up interesting data parts** (*brushing*)
  - utilize **focus+context visualization** to highlight the user selection *consistently(!)* in all views (*linking*)
- Example (interactively?)…
- With base-level IVA, you can already do
  - **feature localization** – *brush high temperatures in a histogram,* for ex.*, and see where they are in spacetime*
  - **local investigation** – for ex.*, select from spacetime and see how attributes are there (compared to all the domain)*
  - **multivariate analysis** – *brushing vorticity values and studying related pressure values* (selection compared to all)

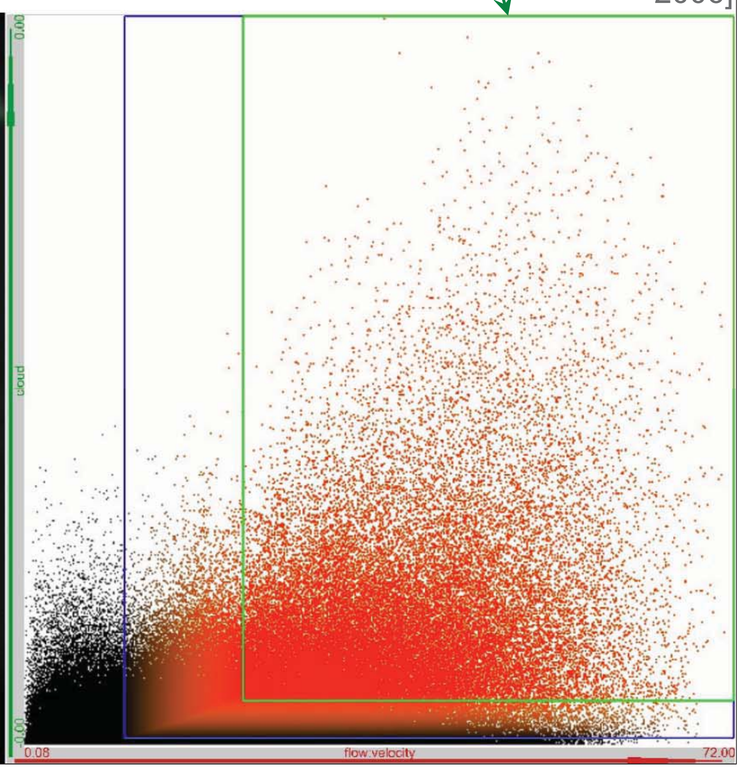
Base-level IVA of Flow Data

At least one spatial view & at least one attribute view

→ studying different aspects of flow data

[Hauser, 2006]





Getting more out of IVA (advanced IVA)

- Starting from base-level IVA,
  - we enable the **identification of complex features**, for ex., by exploiting a *feature definition language* — level 2
  - we realize **advanced brushing schemes**, e.g., by realizing a *similarity brush*
  - we facilitate **interactive attribute derivation**, e.g., by means of a *formula editor*
  - we **integrate statistics/ML on demand**, e.g., by *linking to R*

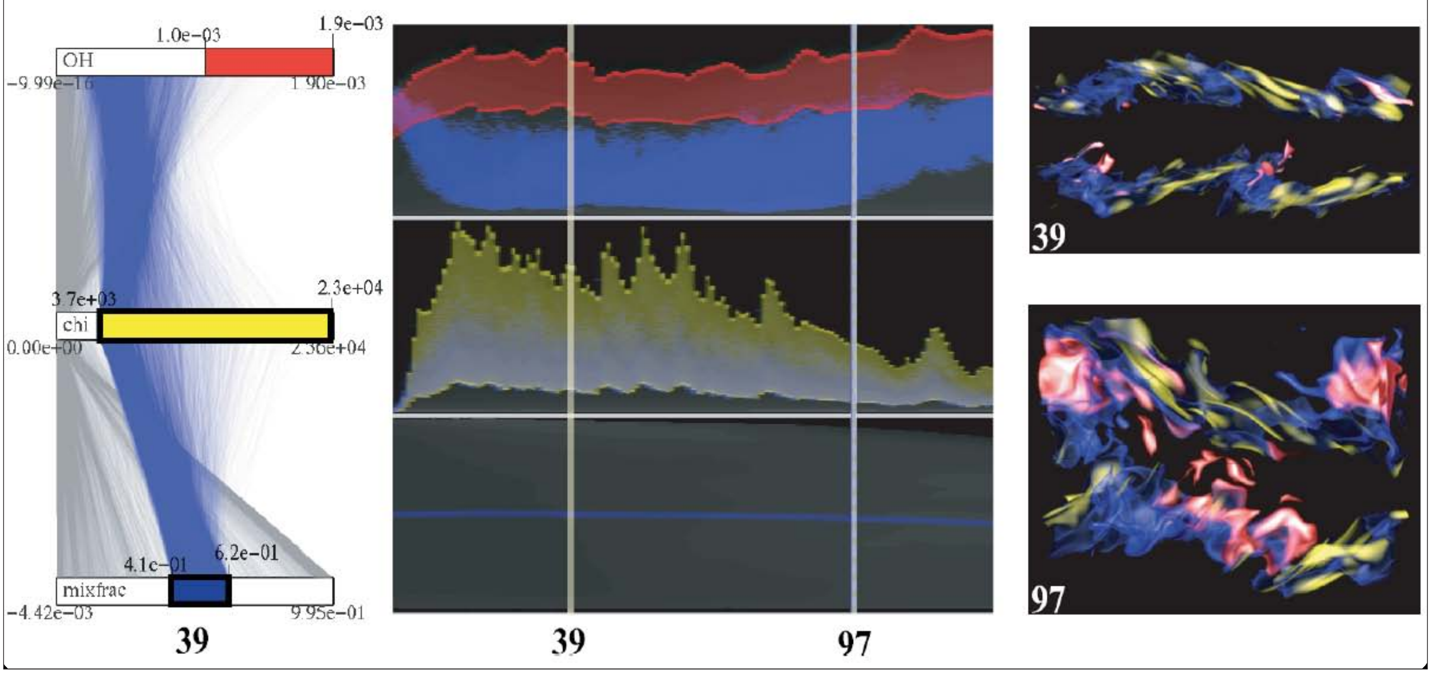
  (the previous three items: level 3)

- With advanced IVA,
  - we **drill deeper** (data→selections→features→…)
  - we **read between the lines** (semantic relations)
  - **answer complex questions** about the data

Low-level IVA of Flow Sim. Data

Multiple selections in parallel coordinates
plus a time-histogram
and linked volume rendering
(colors according to the selections)

[Akiba & Ma, 2007]



Flow Simulation Data and IVA

- Data from computational simulation, *e.g.*, CFD, is
  - usually given on (large & interesting) **spatial grids** (often also **time-dependent**)
  - often **multivariate** in terms of the simulated values
  - based on a **continuous model**
- Considering such data in the **d**(**x**) form
  - with **d** being the **dependent variables** (the simulated **variates**), for ex., velocities, pressure, temperature, …
  - and **x** representing the **independent variables**, *i.e.*, the **domain** of the data (usually space and time)
- With IVA,
  - we **relate x and d** (feature localization, local investigation) as well as $\mathbf{d}_i$ **and** $\mathbf{d}_j$ (multivariate analysis)
  - we consider **δ**(**d**), *i.e.*, derived "views" on the data
    - either explicitly (by attribute derivation)
    - or implicitly (by advanced interaction mechanisms)

Derived "Views" (higher-level IVA) – local

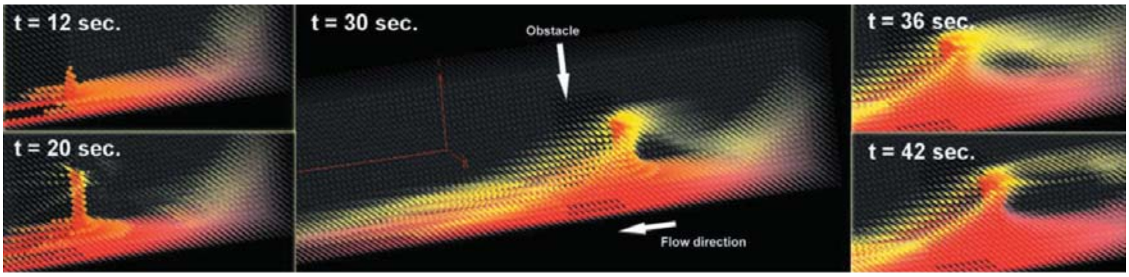
- **Local** [vs. non-local (semi-local, global)] derivations
  - considering **derivatives**, e.g., wrt. space/time, incl.
    - **temporal derivatives** $\mathbf{d}_i'$ ($d\mathbf{d}_i/dt$) // Eularian view
    - **spatial derivatives** $\nabla\mathbf{d}_i$ ($d\mathbf{d}_i/d\mathbf{x}$), in particular also the spatial velocity gradient $\mathbf{J}=\nabla\mathbf{v}$ ($d\mathbf{v}/d\mathbf{x}$)
  - **vector calculus** based on —"—, inc.
    - **divergence** div $\mathbf{v}$ ($\nabla\cdot\mathbf{v}$)
    - **rate of strain** $\mathbf{S} = (\mathbf{J} + \mathbf{J}^\top)/2$
    - **curl** (vorticity) $\boldsymbol{\omega}$ ($\nabla\times\mathbf{v}$)
    - rate of rotation $\boldsymbol{\Omega} = (\mathbf{J} - \mathbf{J}^\top)/2$
  - **local feature detectors**, *e.g.*, based on —"— [Bürger et al., 2007]
    - **vorticity magnitude** $|\boldsymbol{\omega}|$ [Strawn et al., 1998]
    - **normalized helicity** [Levy et al., 1990] $H_n = \dfrac{\mathbf{v}\cdot\omega}{|\mathbf{v}|\cdot|\omega|}$
    - **Hunt's Q** [Hunt et al., 1988] $Q = \|\boldsymbol{\Omega}\|^2 - \|\mathbf{S}\|^2$
    - **kinematic vorticity number** [Truesdell, '54] $N_k = \|\boldsymbol{\Omega}\| \,/\, \|\mathbf{S}\|$
    - λ_2 according to Jeong & Hussain (1995) $\lambda_2(\boldsymbol{\Omega}^2 + \mathbf{S}^2)$

Derived "Views" (higher-level IVA) – non-local

- **Non-local** (semi-local, global) **derivations**
  - **local neighborhoods** $\mathbf{P}_r(\mathbf{x}) = \{\, \mathbf{y} \mid |\mathbf{x}-\mathbf{y}|<r \,\}$
    - **local neighborhood statistics** [Angelelli et al., 2011], like also moving averages, for ex.
    - **stream-/streak-/pathlet statistics** (*e.g.*, averages)
    - **local normalization**
    - *etc.*
  - **global methods**
    - **reconstructions from scale-space representation**, *e.g.*, POD-based reconstruction [Pobitzer et al., 2011]
    - **topology-based approaches**, *e.g.*, uncertain vector field topology [Otto et al., 2010 & 2011]
    - **integration-based approaches**, *e.g.*, FTLE computation

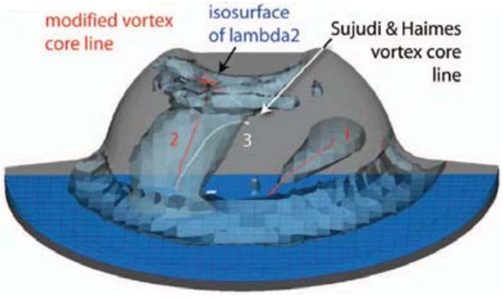
Analyzing the Change over Time

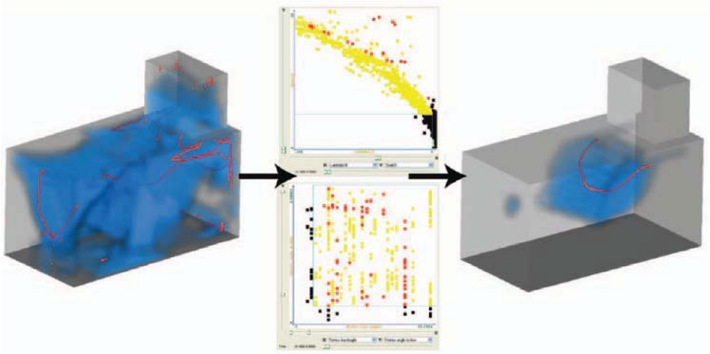
- To access unsteady aspects of flows, [Doleisch et al., 2006]
  - we look at **temporal changes** $d\mathbf{d}_i/dt$, for ex., approximated by central differences, possibly computed after some temporal smoothing
  - we derive **time-step-relative normalization** ($\mathbf{d}_i$ normalized to [0,1] per time-step, also zero-preserving)
  - we allow the **interpolation of selections over time** (like in keyframe animation)
  - we provide a **measure of how stationary a $\mathbf{d}_i$ is** (for how long it stays within an ε-neighborhood)
  - we provide a **measure to capture local extrema** (both maxima of $\mathbf{d}_i$ as well as minima of $\mathbf{d}_i$)



Unsteady Vortex Extraction with IVA

- Going unsteady in vortex extraction: [Fuchs et al., 2008]
  - Based on the approach by Sujudi & Haimes (1995), *i.e.*, to search where $\boldsymbol{\varepsilon}_r || \mathbf{v}$ (eigenvector corresponding to the only real eigenvalue of $\nabla \mathbf{v}$),
  - and a re-formulation [Peikert & Roth, 1999] as $\mathbf{a}_E || \mathbf{v}$ (with $\mathbf{a}_E = (\nabla \mathbf{v})\mathbf{v}$, only for $\nabla \mathbf{v}$ with only one real eigenvalue),
  - we can now search for all places with $\mathbf{a}_L || \mathbf{v}$ (with $\mathbf{a}_L = D\mathbf{u}/dt$, *i.e.*, the particle acceleration $(\nabla \mathbf{v})\mathbf{v} + d\mathbf{v}/dt$)
  - higher-order [Roth & Peikert, 1998] $\mathbf{b}_E || \mathbf{v}$ ⇨ $\mathbf{b}_L || \mathbf{v}$ ($\mathbf{b}_L = D^2\mathbf{u}/dt^2$)

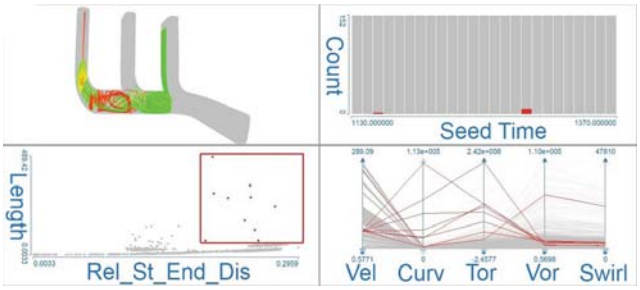


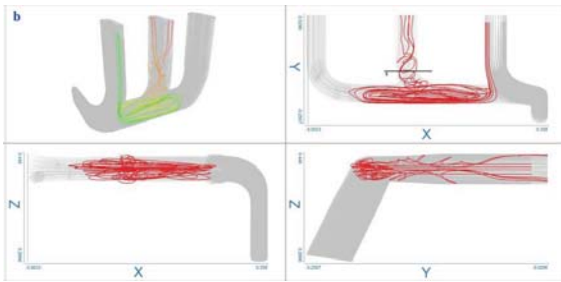


Pathline Attributes and IVA

[Shi et al. 2009]
[Lež et al., 2011]

- Getting insight into flow via pathlines and their attributes
  - we compute pathlines and various pathline attributes describing their local and global behavior
  - we use IVA to explore the attribute space
  - many parameters computed – scalar and time dep.
  - multi-step analysis introduced – start with coarse pathlines, refine where necessary
  - projections of pathlines to 2D planes used for interaction



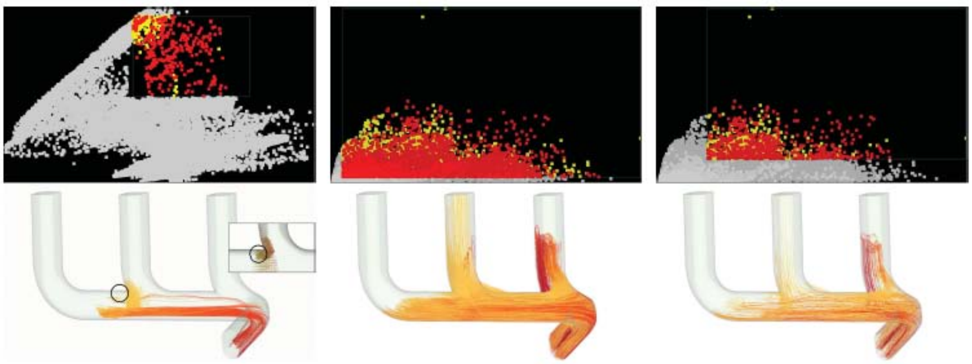


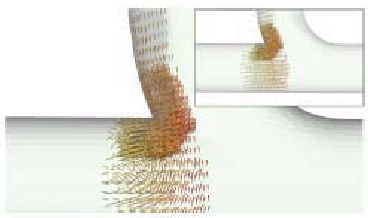
Factor Analysis of Pathline Attributes IVA

- Main problem with parameters – parameter selection
  - statistical analysis in order to select relevant parameters

[Pobitzer et al. 2012]

  - find an universal starting set of parameters
  - six data sets analyzed (5 simulated, 1 analytical)
  - six attributes identified (1 related to shape, 1 to vortices, 4 to motion) which for a common expressive set for analysis of all data sets





Conclusions

- IVA helps to integrate the user's and the computer's strengths to enable exploration and analysis
- IVA is interactive and iterative
- An approach to realize semantic abstraction from data (to features, insight)
- Enables the joint analysis based on multiple perspectives, e.g., several feature detectors
- Helps with questions of different character (physical, geometric, statistical, …)
- Non-trivial integration of Eularian and Langrangian data for IVA

Acknowledgements

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  Question?
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- R. Peikert, H. Theisel, *et al*.
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